# Human Performance Evaluation of Manipulation Schemes in Virtual Environments

Shumin Zhai & Paul Milgram
Ergonomics in Telerobotics and Control (*Etc*) Lab
Department of Industrial Engineering, University of Toronto, Toronto, Canada M5S 1A4
email: shumin@virtual.rose.toronto.edu / milgram@gpu.utcc.utoronto.ca

**Abstract**

This paper presents the results of one of the first experiments in a research programme aimed at systematically investigating manipulation schemes for spatial input, from a human factors point of view. A three dimensional design space model is proposed as a framework for such investigations and four options within this model are tested in a 6 degree-of-freedom target acquisition task within a virtual environment. Experimental results indicate strong performance advantages for isometric sensing combined with rate control and for isotonic sensing combined with position control. A strong interaction between sensing mode and mapping function is found. The findings are discussed in relation to the literature on spatial manipulation.

## 1. Introduction

Although a great deal of research on spatial manipulation has been carried out, in relation to the fields of human-computer interaction [e.g. Buxton, 1990], telerobotics and teleoperation [e.g. Brooks & Bejczy, 1985], and classical tracking / manual control [e.g. Poulton, 1974], it is only recently that the importance of this topic as one of the key components of VR (virtual reality) has been recognised [Zeltzer, 1992; Wickens, 1992]. A number of 6 degree-of-freedom (6DOF) sensors, such as the Spaceball™, the Polhemus™ and the Ascension Bird™, have been developed to support such manipulation, and a number of studies have been carried out to evaluate user performance when manipulating 3D graphical objects with these 6DOF input devices. For example, Massimino et al [1989] evaluated an isometric controller in a 6DOF placement task. Ware [1990] conducted a similar study with a Polhemus™ device in various display modes. Sturman [1992] compared 'whole hand input' with buttons and dials. Research currently underway at the University of Toronto aims at addressing this topic systematically, by investigating a variety of factors involved in the process of manipulating objects in 3-space. This paper presents the results of one of the first experiments in that programme.

## 2. Systematics in 6DOF manipulation

Designers of interfaces for spatial manipulation are often faced with a large variety of potential forms and uses of available devices. Just as the zoologist must apply systematics to deal with the tremendous diversity of wildlife in nature [Mayer & Ashlock, 1991], so must the interface researcher invest efforts toward the development of a suitable taxonomy or model of design options. Although a number of taxonomies have in fact been proposed to define existing interaction techniques [e.g. Buxton, 1983; Foley et al, 1984; Card et al, 1990], these have focussed primarily on classifying more conventional 2DOF input devices, such as the mouse and the trackball.

Figure 1 presents a geometric model which defines a three dimensional[1] subset of the conceptual space that we are exploring and provides a framework for studying multi-degree-of-freedom manipulation schemes in 3-space. Three taxonomic elements, i.e. mapping relationship, sensing mode and degree of integration, have been chosen for consideration due to their importance in determining user behaviour in manipulating 3D objects.

[1] The fact that both the model of Figure 1 and the task manipulation space are three dimensional is coincidental. The axes of the model in the figure represent three of the critical dimensions of a larger n-dimensional taxonomy of input devices.

The X axis in Figure 1 defines a continuum of different *mapping relationships* (or transfer functions) between the user's limb and the resulting movement of an object being manipulated, including translations and rotations. Near the origin of the X axis is where the output of the user's limb is mapped to object position or orientation by a *pure gain*. This is often referred to in the dynamic tracking literature as *position* control, or *zero order* control [e.g. Poulton, 1974]. At the outward end of the X axis shown here is where the transfer function is a first order *time integration*, otherwise known as *rate* or velocity control. Higher order integration (acceleration control) is also conceivable, but can become difficult to control, or even unstable.

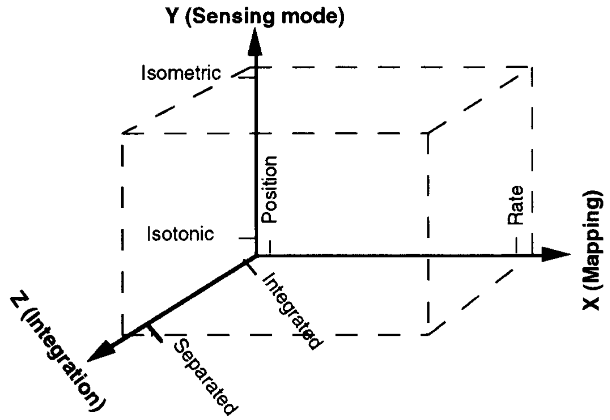


Figure 1. A framework for studying (multi-degree-of-freedom) manipulation schemes

The Y dimension of the model represents the *mode of sensing*, or transduction of the output of the user's limb. The two extremes shown here are *isotonic*[1] sensing and *isometric*[2] sensing. The region between the extremes can be thought of as spring-loaded elastic sensing.

The third dimension of the model, pictured along the Z axis, is the *degree of control integration*. The origin here represents *fully integrated* control (6DOF), while the other extreme represents *completely separated* control (i.e. six 1DOF controllers). Between the extremes of the Z axis would lie the option of two 3DOF controllers, one for rotations and one for translations, which is the way that some telerobots are controlled.

The model in Figure 1 describes a sub-space for conceptualising the design of multi-DOF manipulation interfaces, where the specification of any particular manipulation interface can be characterised by a set of {x,y,z} parameters. Obviously, as we move from one point in this framework to another, the expected behaviour of users manipulating 3D objects will change. Corresponding to these changes is the need to determine whether their *performance* will change also and, if so, in what manner. Some indication of expected performance changes within the design space can be found in part within the existing literature; however, further experimental research must be conducted in order for us to have a more complete understanding. The remainder of this paper

---

[1] *isotonic*: of, relating to, or being muscular contraction in the absence of significant resistance, with marked shortening of muscle fibers, and without great increase in muscle tone -- compare ISOMETRIC. (*Webster's Ninth New Collegiate Dictionary)*

[2] *isometric*: of, relating to, or being muscular contraction against resistance, without significant shortening of muscle fibers and with marked increase in muscle tone. (*Webster's Ninth New Collegiate Dictionary)*

presents an experimental investigation of user performance at four corners of the X-Y plane (mapping and sensing) shown in the model, for a 6DOF positioning task.

## 3. Experiment

### 3.1. Experimental Platform

The experiment was conducted using the MITS (Manipulation in Three Space) system[1], developed by the authors at the University of Toronto. MITS is a non-immersive stereoscopic virtual environment developed on a SGI IRIS 4D/310 GTX graphics workstation, equipped with a Spaceball™, an Ascension Bird™, CrystalEyes™ stereoscopic glasses and some self designed controllers. MITS allows the user dynamically (>15 HZ update rate) to manipulate a variety of 3D objects with 6 degrees of freedom using various display and control modes.

### 3.2 Experimental conditions --- manipulation schemes

Four 6 DOF manipulation schemes representing each corner of the X,Y plane shown in Figure 1 were tested in the experiment. These were, in a counterclockwise direction around the XY plane: *isotonic* sensing with *position* control, *isotonic* sensing with *rate* control, *isometric* sensing with *rate* control and *isometric* sensing with *position* control. In relation to the Z axis, all 6DOF manipulation schemes were fully integrated.

The *isotonic position* scheme is implemented by means of a MITS glove, which consists of an Ascension Bird™ sensor and a button (clutch) mounted on a bicycle glove. It senses the user's hand location relative to a starting position, at which the hand starts to close (adduction), and maps the distance travelled (both translational and rotational) onto the virtual 3D object movement. While the hand is closed, the moving object follows the hand motion; while the hand is opened, the manipulated object remains fixed.

The *isotonic rate* scheme functions the same way as *isotonic position* does, except that the hand motion is mapped to the manipulated object by integration over time. This means that movement of the hand directly controls the *velocity* of the manipulated object. The farther the hand travels after adduction, the faster the object moves. When the hand is opened, the velocity drops to zero and the object stays wherever it is.

The *isometric rate* scheme operates by detecting the forces and torques that the user applies to a Spaceball™ and maps them onto the 3D object position and orientation by integration over time. Again, this is velocity control.

The *isometric position* scheme maps the force and torque that the user applies to the Spaceball™ onto the 3D object position by a pure gain. Because the isometric Spaceball™ is a self centring device, whose output returns to zero when external force is released, a constant force would have to be maintained in order to keep an object in place. This problem is resolved by using the button on the Spaceball as a clutch, such that force is mapped to position only when the button is kept pressed. Whenever the button is released, the object stays in the place where it was before the release.

It was found that performance with each manipulation scheme is a function of the sensitivity setting (control gains). The relationship between task completion time and sensitivity typically appears as a U-shaped function when log control gain is plotted. Taking *isometric rate* control as an example, Figure 2 shows a well practised user's mean task completion times (over 15 trials) for different sensitivity settings. Note that there is a wide range of settings at the bottom of the U, for which performance differences are not statistically significant. The control gain used in the experiment for the isometric rate condition was set at the middle of that region. The other control schemes were optimised through similar systematic parameter searching, with one experienced user as subject.

---

[1] The authors will be pleased to provide software to parties interested in extending this area of research.

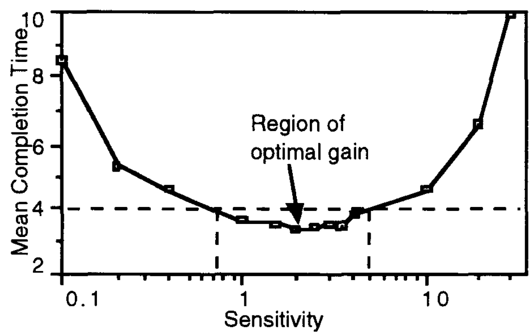


Figure 2. Time performance as control gain varies

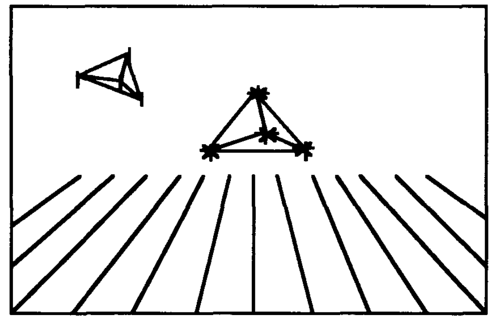

Figure 3. Experimental task

3.3 Experimental Task

Figure 3 illustrates the task used in the experiment. Our aim in designing this task was to incorporate 6 degrees of freedom of manipulation and yet be simple enough to be generalisable to various applications, including *virtual control* in telerobotics [Zhai & Milgram, 1991]. In the experiment, subjects were asked to move the tetrahedron appearing away from the centre as quickly as possible to align it with the target tetrahedron in the centre of the screen. The tetrahedrons edges and vertex markers (bars and spherical stars) were coloured so that there was only one correct match in orientation. The markers superimposed at each corner of the tetrahedrons served three purposes: the vertical bars on the moving object were to enhance stereoscopic perception, while the stars on the target tetrahedron indicated the acceptable target volume for the task. The two types of markers (stars and bars) served also to differentiate the target from the moving object. Whenever a corner of the moving object reached the corresponding star of the target, the corresponding star changed its colour as an indication of capture. If all four corresponding corners stayed matched for 0.8 seconds, the trial was completed. At the end of each trial, the trial number and time score were printed on the screen, in order to keep subjects motivated. The task was well explained before the first session and a questionnaire was filled in by each subject after the last session.

Since the purpose of the research programme is explicitly to evaluate 6DOF manipulation schemes, our emphasis in designing the display was to provide the largest possible number of 3D spatial cues, in order that any bottlenecks in performance of the task would result most likely from the particular manipulation scheme and not from the display. The display consisted of a 120 Hz sequential switching stereoscopic image, which has been shown to be a necessary feature for this kind of experiment, because without stereopsis, much more orientation ambiguity would be perceived by the subjects. To enhance the 3D effect, wide angle perspective projection and interposition cues were also adopted. The tetrahedrons were drawn in wire-frame so that all edges and corners of the objects could be perceived simultaneously. Subjects were asked to sit on a chair 60 cm away from the computer screen.

3.4 Subjects

Eight paid volunteer subjects participated in the experiment. All subjects were screened with a Bausch & Lomb Orthorater. Two of the original ten applicants were rejected, one for having poor stereopsis and one for having poor (corrected) near vision. All of the eight accepted subjects were (incidentally) male and right handed, as determined by the Edinburgh inventory. Four of them were engineering undergraduate students, three were engineering graduate students, and one was a software engineer. All of the subjects had experience with a mouse but none had previous experience with 6DOF input devices. All subjects were asked to use their dominant hand to manipulate the input devices. Subjects' ages ranged from 20 to 40.

3.5 Experimental Design and Procedure

Each subject participated in four separate experimental sessions ranging over four consecutive days. Each 40 minute session involved only one of the four manipulation schemes and was divided into four stages. Each stage comprised 10 minutes of training, followed by 12 trials of data collection. Each training stage consisted of demonstrations and suggestions by the experimenter, combined with practice trials. The data from the 12 trials were grouped into 3 blocks of 4 trials, each block comprising 4 different randomly shuffled starting locations for the manipulated object. Block mean times were used as the dependent variable. After every set of 12 recording trials, the mean completion time was shown to the subject.

A within subjects design was used in the experiment. In order to minimise skill transfer (either positive or negative) from one scheme to another [Poulton 1974], three preventive measures were taken. First, different manipulation schemes were tested on different days, so that different conditions for any one subject were at least 12 hours apart. Second, the 10 minute practice and training sessions preceding the first set of data collection trials served as a buffer to reduce transfer from the session of the previous day. Third, the order of the four schemes being tested was counterbalanced over the eight subjects by using two Latin square patterns, which resulted in every technique being presented an equal number of times as first, second, third or fourth condition.

**4. Results**

Figure 4 presents mean completion times from the four stages of data collection. It shows that performance for all schemes improves as practice increases. Comparatively, the *isometric position* and the *isotonic rate* control were inferior to the other two schemes. During the first stage of the experiment (10 minutes training period), the *isotonic position* scheme was slightly faster than *isometric rate* ($p=.051$), which supported our expectation that, being the most intuitive manipulation scheme, the *isotonic position* mode would be easier to learn than the *isometric rate* mode. However, the superiority of *isotonic position* control over *isometric rate* control disappeared after 20 minutes practice (Figure 4).

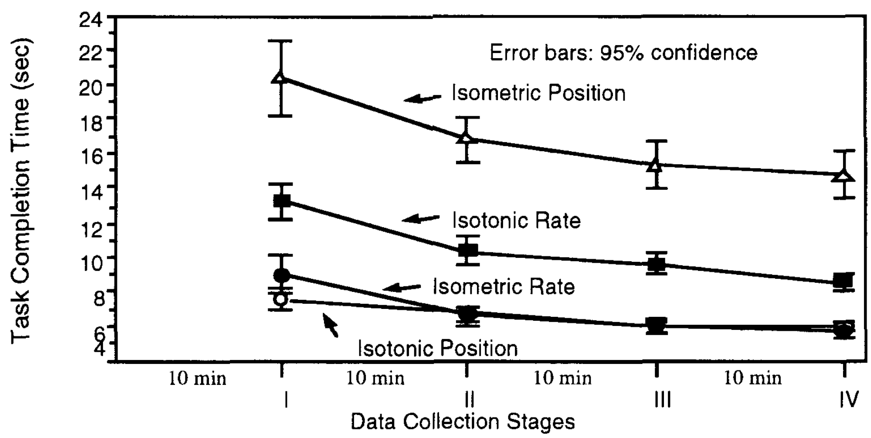


Figure 4. Mean completion times over four stages of data collection

Performance during stage IV is of most interest to us, as at this stage subjects have had 40 minutes of intensive practice. Using the data in stage IV, analysis of variance shows that subjects ($F(7,340)=26.7$, $p<.0001$), manipulation schemes ($F(3,340)=264.2$, $p<.0001$), initial locations of the object being manipulated ($F(3,340)=3.39$, $p<.018$), as well as interaction between subjects and manipulation schemes ($F(21,340)=17.9$, $p<.0001$), are all statistically significant factors. These results are illustrated in Figure 5.

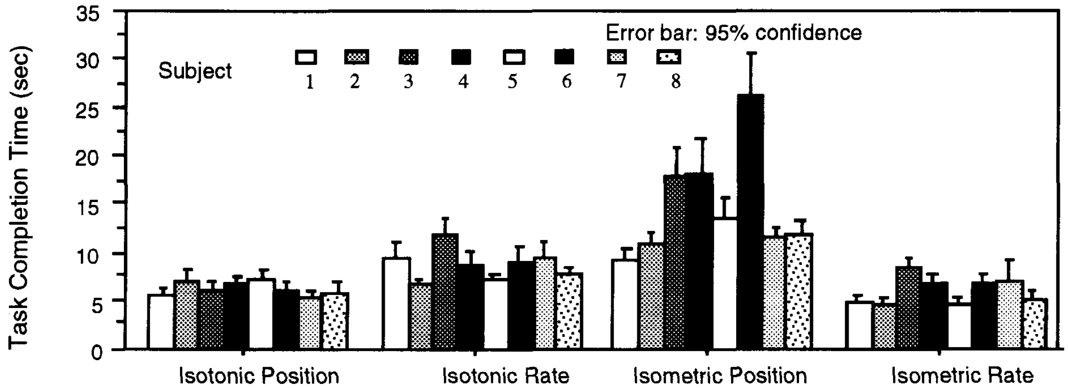


Figure 5. Mean completion times for all eight subjects, for each control scheme, during stage IV

Referring back to Figure 1, the proposed design space framework, a strong interaction ($p<.0001$) was found between the X dimension (mapping) and the Y dimension (sensing mode), as illustrated in Figure 6. Clearly in this experiment performance was better only when *isometric* sensing was combined with *rate* control or when *isotonic* sensing was combined with *position* control. The important practical implication of this result is that to formulate an interface design decision based simply on comparing sensing mode or mapping function would be very misleading.

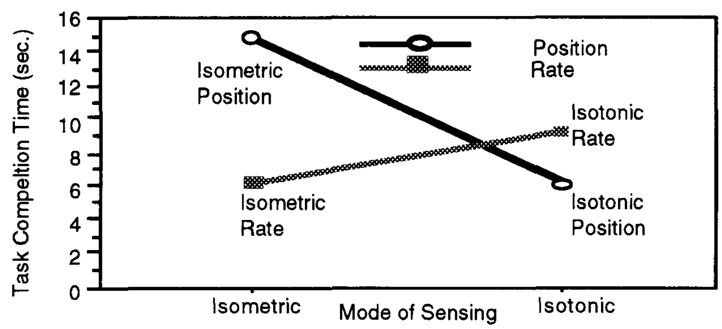


Figure 6. Interaction between sensing mode and mapping function

## 5. Discussion

Our research on patterns of performance for 6DOF positioning tasks extends much of the earlier research in the literature, which is centred primarily on 1, 2 or 3 DOF controls [e.g. Poulton, 1974; Card et al, 1978; Kim et al, 1987; Dunbar et al, 1983]. Due to space constraints, we shall discuss only our major findings in relation to some of the earlier research.

Kim et al [1987] compared rate control versus position control in a 3DOF (translation only) placement task. They found that, under all conditions tested, including force (isometric) joystick and displacement joystick, position control yielded consistently better performance than rate control, even though some interaction between sensing mode and mapping function was reported. Because their experiment involved only 2 subjects and 3DOF, however, direct comparison with our current 6DOF manipulation study, in which we do find an interaction between mapping function and sensing mode (Figure 6), is difficult.

With regards to the Y dimension (sensing mode) of Figure 1, earlier research comparing isometric sensing and isotonic sensing, in the context of 1 or 2 DOF manual tracking, is well reviewed in [Poulton 1974]. Poulton's hypothesis was that isometric sensing is an advantage when time is short,

but a disadvantage when accurate positioning is required because it does not provide the human operator with displacement cues proportional to its output, as an isotonic sensing control does. However, out of 17 research reports cited by Poulton, 12 strongly favour isometric sensing ('pressure control' in his terminology), 2 slightly favour isometric sensing and only 3 slightly favour isotonic sensing ('moving control' in his terminology). For our purposes, we find once again that simple comparisons between sensing modes can be misleading, due to strong apparent interactions between mapping function and sensing mode.

## 6. Future research

This is the first in a series of experimental investigations of 6DOF spatial manipulation mechanisms and strategies. We have begun with one plane of the 3D model in Figure 1, using a static target acquisition task. In addition to exploring other options in that design space, such as separated controls, follow-up research is being conducted to investigate dynamic tracking performance. Theoretical analysis of different proprioceptive feedback modalities is also underway. In addition, other than task completion time as a performance measure, many more criteria have to be considered for designing or selecting a manipulation interface. One such consideration is that in general isometric controllers have much smaller operating volumes than isotonic controllers (similar to the 'footprint problem' associated with 2DOF input devices [Buxton, 1990]). Other factors which we intend to analyse include fatigue and subjective preferences.

Acknowledgement: The authors would like to thank W. Buxton, J.W. Senders, D. Drascic, Y. Xiao, and others at the University of Toronto for their valuable input. This work is partially supported by both contract W7711-7-7009/01-SE with DCIEM, Toronto with Dr. J. Grodski as scientific authority, and the Canadian Natural Sciences and Engineering Research Council (NSERC).

## References

Brooks, T.L. & Bejczy, T.L., 1985, Hand controllers for teleoperation, a state of the art technology survey and evaluation, *JPL Publication* 85-11.

Buxton, W., 1983, Lexical and pragmatic considerations of input structures, *Computer Graphics*, Vol.17, No.1, 31-37.

Buxton, W., 1990, The pragmatics of haptic input, Tutorial 26 Notes, *CHI'90, ACM Conference on Human Factors in Computing Systems,* Seattle, Washington.

Card, S.K., English, W.K.& Burr, B.J., 1978, Evaluation of mouse, rate controlled isometric joystick, step keys and text keys for text selection on a CRT, *Ergonomics*, 21, 601-613.

Card, S., Mackinlay, J.D. & Robertson, G.G. 1990, The design space of input devices. *Proc.* of *CHI'90, ACM Conf. on Human Factors in Computing Systems,* Seattle, Washington.

Dunbar, S., Hartzell, E.J., Madison, P.& Remple R., 1983, Helicopter integrated controller research, *Proc. of the Nineteenth Annual Conference on Manual Control,* Cambridge, MA.

Foley, J.D., Wallance, V.L. & Chan,P., 1984, The human factors of computer graphics interaction techniques. *IEEE Computer Graphics & Application,* Vol.4, No.11, 13-48.

Kim, W.S., Tendick, F., Ellis, S.R., & Stark L. W., 1987, A comparison of position and rate control for telemanipulation with consideration of manipulator system dynamics, *IEEE Journal of Robotics and Automation*, Vol. RA-3, No.5, 426-436.

Massimino, M. J., Sheridan, T.B, and Roseborough, J. B., 1989, One hand tracking in six degrees of freedom, *Proc. IEEE International Conf. on System, Man, Cybernetics* , 498-503

Mayer, E. & Ashlock, P.D., 1991, *Principles of Systematic Zoology,* 2nd ed, McGraw-Hill, NY.

Poulton, E.C., 1974, *Tracking skill and manual control,* Academic Press, New York.

Sturman, D., 1992, *Whole Hand Input,* PhD Dissertation, MIT Media Lab.

Ware, C., 1990, Using hand position for virtual object placement, *The Visual Computer*, 1990, No.6, pp 245-253.

Wickens, C.D., 1992, Virtual reality and education, *Proc. IEEE International Conf. on System, Man, Cybernetics* , Chicago, 842-847.

Zeltzer, D., 1992, Autonomy, interaction, and presence, *PRESENCE - Teleoperators and Virtual Environments,* Vol.1, No.1, 127-132.

Zhai, S. & Milgram, P., 1991, A telerobotic virtual control system, *Proceedings of SPIE, Vol. 1612, Cooperative Intelligent Robotics in Space II,* Boston, 311-320.

Zhai, S., Milgram, P. & Drascic, D., 1993, An evaluation of four 6 degree-of-freedom input techniques, *Adjunct Proc. InterChi'93: ACM conference on Human Factors in Computing Systems*, April 1993, Amsterdam, 123-124.